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Text segmentation of the Archimedes Palimpsest using remote sensing techniques

Charles Dickinson

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Text Segmentation of the Archimedes Palimpsest
Using Remote Sensing Techniques

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A thesis submitted in partial fulfillment of the requirement for the degree of a Master of Science in the Chester F. Carlson Center for Image Science of the College of Science Rochester Institute of Technology

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Text Segmentation of the Archimedes Palimpsest
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Text Segmentation of the Archimedes Palimpsest
Using Remote Sensing Techniques

Charles Dickinson

Submitted to the Chester F. Carlson Center for Image Science of the College of Science
in partial fulfillment of the requirement for the degree of Master of Science at the
Rochester Institute of Technology

Abstract

Digital imaging methods have been developed and adapted to analyze the
so-called "Archimedes Palimpsest", which is a 10th century overwritten manuscript
including the oldest known copies of seven of the treatises of Archimedes.
Multispectral digital images of five of the leaves of the palimpsest have been
collected, processed, and analyzed using principal component analysis and orthogonal
subspace projection techniques. These methods have been applied to "strip off" the later
overwriting to reveal the original text.
Acknowledgement

The author would like to thank Roger L. Easton, his thesis advisor. Participation in this research has been a great honor and privilege. The author would also like to thank Dr. Keith Knox and Dr. Robert Johnston for being on his thesis committee. Finally, the author would like to thank Mr. Will Noel and Ms. Abigail Quandt from the Walters Art Museum, in addition to the owner of the Archimedes Palimpsest. Without them, this research would not have been possible.
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Chapter 1: Introduction

The deciphering and translating of ancient documents with the aid of imaging technology began with the simple magnifying glass. The magnifying glass eventually gave way to the silver halide photograph because of its high resolution and archival nature. Today, digital imaging is taking over from traditional photographs. Digital imaging of ancient documents holds great promise because the images can be manipulated to extract all existing image information to aid in their translation. In addition, having the document images in digital format allows for even greater archivability with the advent of CD writers.

The degradation of ancient manuscripts is a very common problem. The writing surface is typically an organic material that will decay if left untouched. This is typically the least of the scholar's worries, however, because most documents older than a few hundred years have a history of charring, staining, mold, and/or intentional removal of text. These problems can seriously compromise the readability of a document. At this point it becomes necessary for the translator to employ equipment beyond the human eye to decipher the text.

Photography has been a major tool for improving the readability of document artifacts for many years because of its many advantages. First, it minimizes the physical contact with the artifact itself. Many ancient manuscripts are very fragile, so it is much preferable to examine a replica rather than the artifact itself. Second, photographs are easily reproducible with little loss in quality. This makes the manuscripts available to large numbers of scholars around the world, rather than only to those with direct access. The images may be archived by storing the negatives. Finally, one can use the wider
range of photographic sensitivity to see things invisible to the eye. This can be done by filtering the input to the camera so that it sees only a portion of the EM spectrum. In addition to this the spectrum of light reflecting off the document can be altered by changing the illumination. The combination of these two techniques produce photographs that look very different than the visual appearance. If one or more of the filter/illuminant combinations produce better visibility, then the document image is more readable to the scholar.

In recent years, the technologies of the personal computer (PC) and the digital camera have come into the forefront. These two technologies are beginning to be used in the field of archeology and show much promise in this application. By creating digital images of the artifacts, a large number of opportunities are facilitated. First, digital images are even easier to distribute amongst scholars. Also, the images may be stored without a controlled environment. Perhaps the most important adjunct of digital photography is digital image processing which allows the images to be manipulated in to extract the greatest amount of information possible from ancient document images. Combine this with the ever accelerating processing speeds of today’s PCs to see the power of digital photography in the imaging of manuscripts.

The deterioration of manuscripts is an unfortunate tragedy because they were created to preserve the most important thoughts of the culture. The history of the human race is of the utmost importance to us because of the simple fact that we are humans and we want to know as much about ourselves as possible. The written word allows us not only to look at our past, but to learn from it. Many documents from antiquity have been lost forever, which is why it is so important to gain as much as possible from those that
are currently available. Unfortunately, many documents that are being imaged without utilizing existing technologies that could be invaluable in their translation. It is for these reasons that research in this area is so important. Regrettably, little has been published on the subject. The goal of this research is not only to aid in the deciphering of the Archimedes Palimpsest, but also to further knowledge about the field and to attract attention to it.

This paper will describe two areas of research regarding the Archimedes Palimpsest: the imaging of the document, and an assessment of the processing used. As previously mentioned, one of the primary ways to extract information from the documents is to use filters and illuminants which hopefully show features that the eye cannot see. This method is the focus of the first area of research presented. The data captured from the palimpsest is multispectral, i.e. the images were collected in several colors. As such, many remote sensing techniques are applicable to the images. The focus of the second area of research is two remote sensing algorithms, principal component analysis and orthogonal subspace projection. The parameters of these algorithms are adjusted and compared to each other.

The layout of this paper is as follows. Chapter 2 contains background about the palimpsest, digital and multispectral imaging, the algorithms, and a literature review about similar work being done and the algorithms themselves. Chapter 3 will discuss the experimental procedure. Chapter 4 will present the results of these experiments, and Chapter 5 will make some conclusions about the research.
Chapter 2: Background and Literature Review

This chapter is divided into four sections. The first describes the Archimedes Palimpsest and the principles of the image capture modality used in this research: digital cameras, multispectral data, illuminants, and liquid crystal tunable filters. The second section reviews the research in the field. Studies have been performed on several works of art and on the Dead Sea Scrolls whose techniques are similar to those employed for the Archimedes Palimpsest. The last two sections describe the processing algorithms used: principal component analysis and orthogonal subspace projection.

2.1: Image Capture

2.1.1: Digital Cameras

The first component in an imaging system is an image capture device. For this application, a digital camera was used. The heart of a digital camera is a photosensitive electronic array, such as a charge-coupled device (CCD). Holst (1996) is an excellent reference on the subject. Holst defines three basic functions of the CCD array: charge collection, charge transfer, and the conversion of charge into a measurable voltage. The CCD is an array of many metal-oxide-semiconductor (MOS) capacitors, also called gates. When light strikes these gates, a number of electron-hole pairs is generated, that is proportional to the number of incident photons. In CCDs, the holes (electron vacancies) are transferred by applying varying voltages to each successive gate in the array, causing the charge to move to the charge collector. The final step is to convert the number of holes into a voltage. This is done with a floating diode which acts as a capacitor. The voltage created by the diode is proportional to the number of holes.
There is also a lens to collect and focus the incident light onto the array, a gain adjustment, and an analog-to-digital converter. Most scientific cameras do not have any built-in image processing algorithms because the data should be as close to the original as possible.

2.1.2: Multispectral Data

The measurement of more than the traditional three spectral bands (RGB) in a digital imaging system is called a multispectral system. The additional spectral bands increase the power of the imaging device to gather data about its target. The typical way to acquire multispectral data is to interpose colored filters between the target and the sensor. While switching filters is not instantaneous, the imaging of a document is time invariant, so this is of little concern.

Pratt (1991) gives an excellent description of multispectral data which is referenced by Kamal, et al. (1999). Pratt first defines an ‘image light function’ which is the light from a scene which enters the detector system. This image light function varies over space, time, and wavelength. However, as previously stated, document imaging is time invariant, so the time variable will be removed. In a multispectral system, the image formed has the following equation:

\[ F_i(x, y) = \int_0^\infty C(x, y, \lambda) S_i(x, y, \lambda) \, d\lambda \]  

(1)

Where \( F_i \) is the \( i \)th spectral image, \( C \) is the image light function, and \( S_i \) is the spectral response of the \( i \)th band sensor. There are several ways to split the spectrum into these bands. In many remote sensing systems, this is done by using a diffracting element of some kind which splits the incoming wavelengths into a spatial dimension. In this application, this is done with filters that pass only certain wavelengths of light.
Pratt goes on to describe the image light function. Reflective objects are have the form:

\[ C(\lambda) = r(\lambda) E(\lambda) \]  (2)

Where \( r \) is the spectral reflectivity of the object and \( E \) is the spectral power distribution of the illumination. The spatial dimensions are removed for simplicity. Similarly, a transmissive object has the form:

\[ C(\lambda) = t(\lambda) E(\lambda) \]  (3)

Where, \( t \) is the spectral transmittance of the object. In truth, all objects have both transmissive and reflective properties when one looks beyond the visible part of the spectrum. An object of this kind would have the following form:

\[ C(\lambda) = r(\lambda)t(\lambda) E(\lambda) \]  (4)

These equations are of great importance to the consideration of multispectral data. If one samples the spectrum with sufficient resolution for the application, one can identify an object by observing how its optical properties vary with spectral band. This is accomplished by creating what is often called a data or image cube. This term refers to an arrangement of the set of images captured of the same scene but varying in spectral band. They are laid ‘on top’ of one another in order of wavelength into a cube. The image data from that scene now has three dimensions, two spatial and one spectral.

Because the pixel values are proportional to the reflectances from the scene, an image cube includes the reflectance spectra of every pixel. These spectra are simple to access by looking at a pixel in the spectral (z dimension) of the image cube. It is therefore possible to compare pixels based on their spectra, and thus to identify the class of the
pixel. The remote sensing community has come up with many algorithms to do this effectively, two of which will be described in sections 2.3 and 2.4.

Kamal (1999) describes another interesting feature about equation (4). If one considers two different pigments lain on top of one another, one pigment will probably obscure the other in the visible spectrum. However, beyond the visible spectrum, e.g. in the infrared region (IR), the pigment on top might be transmissive. This would allow an image to exhibit signal due to the lower level. This fact is of particular importance to the imaging of art, to be discussed in section 3.2.2.

2.1.3: Illuminants

The use of illuminants is an important component in this research. The typical tungsten illuminant covers the visible and the IR regions of the spectrum quite well. Shown in figure 2.1 is the spectral power distribution of CIE illuminant A, an approximation of typical tungsten sources.
Figure 2.1: Tungsten Spectral Power Distribution

The plot shows that a tungsten source is extremely red, in fact its spectral maximum is in the IR region. This is significant because many features of damaged documents and pieces of art are visible in the IR region of the electromagnetic spectrum.

Another spectral region of interest is the ultra violet (UV). Two types of UV illumination are often cited, long- and short-wave UV. These terms represent the peak output of the source being closer to blue (long wave) or further from blue (short wave).

The reason that UV sources are so important to the study of ancient documents is because they can induce ‘fluorescence’, which is the process whereby incident electromagnetic radiation striking an atom excites some electrons into higher energy levels. The electrons emit visible radiation when they fall back to their non-excited state. The character of the fluorescence varies by material. It is well known that parchment fluoresces in the visible spectrum, while most inks do not. This is significant because the
contrast of ink to parchment will increase in visible light images under UV illumination.

Additional benefits can be gained by acquiring multispectral data under UV illumination. This results in images which capture information on how the document is fluorescing in the spectral dimension. Combining multispectral data with different illuminations is a powerful tool for extracting information which is invisible to the human eye.

2.1.4: Liquid Crystal Tunable Filter

One tool used in this project to sample the electromagnetic spectrum at fine intervals is the liquid crystal tunable filter, or LCTF, produced by CRI. The LCTF is a multistage Lyot-Ohman polarization interference filter with a liquid-crystal waveplate at each stage which can electronically vary retardance. A diagram from Slawson et al. (1999) is shown in figure 2.2.

Figure 2.2: LCTF Diagram
In order, the cell contains a linear polarizer, a fixed optical retarder, a liquid-crystal (LC) waveplate which varies in optical retardance, and finally another linear polarizer whose axis is parallel to the original.

The LC waveplate is the heart of this system. It consists of two transparent electrodes sandwiching a cell of nematic liquid crystals as shown in figure 2b, from Slawson et al. (1999). The term 'liquid crystal' refers to a phase of matter that is between a liquid and a crystal. The molecules are rod shaped organic compounds. The initial state of the liquid crystal is such that their long axis is normal to the incoming light. This is altered by applying a voltage to the electrodes, to create an E-field parallel to the light path. Because the liquid crystals are polar molecules, the E-field causes them to twist in that direction. The natural state of the liquid crystals is parallel to the surface of the cell, which causes the crystals to resist this twisting. Therefore, the amount of applied voltage varies the amount of rotation in the crystals, thus varying the retardance.

The polarizer at the end of the cell selects only those wavelengths that have undergone a phase shift of an integer multiple of $\pi$ radians upon passing through the fixed and liquid crystal retarders. To isolate a particular passband, it is necessary to use several such cells in series, where the retardance of each successive cell increases by a factor of 2. The end result is a filter which has a passband centered at a variable wavelength with a bandwidth as small as 10nm.

2.1.5: The Archimedes Palimpsest

The ancient manuscript of concern to this research is the so-called 'Archimedes Palimpsest' which is a bound volume of 177 parchment leaves. The word 'palimpsest'
refers to a document whose original writing has been removed and replaced with new writing. The original 10th century book contained copies of several of the treatises of Archimedes. This book was disbound during the 12th century, the leaves were cut in half, rotated 90 degrees, and re-bound to create a new book of half the size. The original text was scraped off in the process. The ‘new’ bound volume was a Christian prayerbook, called the ‘Euchologion’. The reason for the apparent disregard of the original content was the scarcity of parchment and the fact that the text was scientific, which was considered to be much less important than the religious writing which replaced it.

The Palimpsest today is in poor condition. It has been quite severely stained in some areas, and many of the leaves have suffered from mold. The book contains 74 folded sheets or bifolia and 27 single leaves of original Archimedes text. Of the single leaves, four have been altered further. During the 1930’s, these leaves were vigorously scraped and painted over in the hopes of increasing the value of the book. The combination of the additional scraping and layers of paint present a difficult problem for those who want to read the Archimedes text.

The main goal of both scholars and imaging scientists is to extract as much of the Archimedes text as possible for deciphering. The difficulty of this task is clear, between the original scraping, the distracting Euchologion text, the years of environmental damage, and the paintings made in the 1930’s, there is much work to be done. The silver lining of this project is that no matter how much the original text has been scraped or damaged, there are still trace elements of it left in many regions of the parchment. These trace elements are visible to the naked eye in some regions, and become visible with
digital processing in others. These remnants are still present because of the ink. Iron gall ink contains dyes which sink into the parchment itself, so although the top layer can be removed, the dyes soaked up by the parchment remain.

The true value of the Archimedes Palimpsest is still to be determined. Some of the treatises of Archimedes in the book exist nowhere else, and have not been seen for centuries. However the real promise of Palimpsest is that it will allow scholars to gain insight into the methods used by Archimedes. Archimedes is considered one of the greatest mathematicians of all time, and having a window into his way of thinking is of great interest to both historians and the mathematicians of today.

2.2: Similar Research Areas

2.2.1: Dead Sea Scrolls

Research that preceded the Archimedes project is relevent to this task. Easton, et al. (1995) discusses the application of imaging technology to the Dead Sea Scrolls. Many of these documents had been severely degraded such that the parchment they were written on became black. The scholars had the daunting task of reading dark text on a black background. Efforts to improve the readability of the Dead Sea Scrolls were pursued: simple convolution, color space transforms, and 2-D and 3-D histograms.

Convolution kernels were applied to the papyrus images to smooth the papyrus texture while leaving the text untouched. Next, the background was boosted in pixel value while the text pixel values were decreased. With the texture smoothed and the contrast enhanced, the "Unsharp Mask" filter was applied which enhanced the readability of the text.
Another method used was a color space transform. The RGB image data was transformed into the Xerox "YES" space. This yielded promising results, especially in the "E" channel which is a combination of red and green. This fact is particularly interesting when one considers the nature of the principal components transform, to be discussed in 2.3.

The final tools used were two- and three-dimensional histograms of the RGB data. By comparing histograms of regions of degraded text, non-degraded text, in addition to the parchment, it became possible to segment the image according to the clusters corresponding to these histograms.

2.2.2: Multispectral Imaging of Art

A field which is very much related to archeological imaging is the imaging of pieces of art for scientific data. This kind of research often tries to extract underpaintings, instead of extracting hidden text. Very old pieces of art are 'reconstructed' to estimate their original appearance. Also, it is often of interest to identify the paints that were used, in a non-invasive way. The similarities between this task and archeological imaging are many. Both fields have recognized the necessity to apply segmentation algorithms based on multispectral data. It is clear that these two fields are operating parallel to each other, so it is important to discuss the imaging of art in this paper.

Kamal, et al. (1999) used multispectral image processing to enhance murals painted by the Mayans. This research focused on extending imaging from the visible part
of the spectrum into the IR region. The reasoning for this is that certain materials become very transparent in the IR, while others remain opaque. The goal of the researchers was to improve images of the murals with this additional IR information.

Two methods were employed to enhance the mural images. The first was to use a color space transform on the RGB sensor data to YIQ and HSV spaces. This method is very similar to that used on the Dead Sea Scrolls. At this point the luminance channels (Y and V respectively) were replaced by an IR image, and then transformed back into RGB for display. The other method was to perform a principal component analysis (PCA) on the RGB data, and replace the first component with an IR image. Again, the PCA was then inverted back to RGB data. The results of these two methods yielded promising results which held more detail than the simple RGB renditions of the murals.

Work done by Baronti, et al. (1998) had the different objective of determining the pigments and their quantities in a 16th-century painting. Multispectral images were obtained from the visible to the IR. To create a map of the distribution of the paint materials, it was necessary to perform a PCA on the multispectral data. The PCA components represent the major features in the pigments much more easily than the original data. Two-dimensional histograms were then plotted of the components, and it was found that the pigments clustered quite nicely in this kind of feature space.

### 2.3: Principal Component Analysis

An excellent introduction to the concept of PCA is laid out by Richards (1986). PCA is based on the covariance matrix. As stated in section 2.1.2, a cell of a multidimensional image cube actually provided by the pixel values in each of the
spectral bands. Each pixel spectrum can be represented as a vector in N-dimensional multispectral space, where N is the number of spectral bands. This is illustrated in figure 2.3a and 2.3b, from Richards (1986).

**Figure 2.3a: Uncorrelated 2-D Image Data Example**
Figures 2.3a and 2.3b represent a two-dimensional sensor space with $K$ pixel vectors $\mathbf{x}_j=[(x_j)_1,(x_j)_2]$. The mean position $\mathbf{m}$ is calculated by

$$\mathbf{m} = E\{\mathbf{x}\} = \frac{1}{K} \sum_{j=1}^{K} \mathbf{x}_j$$  \hspace{1cm} (5)

Where $E\{\mathbf{x}\}$ is the expectation operator. The covariance matrix is necessary to describe the 'spread' of the pixels in the multispectral space. The covariance matrix's unbiased estimate is given by

$$\Sigma_x = \frac{1}{K-1} \sum_{j=1}^{K} (\mathbf{x}_j - \mathbf{m})(\mathbf{x}_j - \mathbf{m})^\prime$$  \hspace{1cm} (6)

where $(\cdot)^\prime$ denotes the transpose of the vector $(\mathbf{x}_j - \mathbf{m})$. It is very important to note that the off-diagonal elements of the covariance matrix approach zero if there is little correlation of the data between spectral bands, but they will be large compared to the diagonal.
elements if correlation is significant. The resulting covariance matrices of 2.3a and 2.3b are as follows:

\[
\sum_{2a} = \begin{bmatrix} 2.4 & 0 \\ 0 & 1.87 \end{bmatrix}
\]

\[
\sum_{2b} = \begin{bmatrix} 1.9 & 1.1 \\ 1.1 & 1.1 \end{bmatrix}
\]

As expected, the perfectly uncorrelated data in 2.3a has a covariance matrix with off-diagonal terms of 0, while the correlated data in 2.3b has high off-diagonal terms.

PCA is intended to find some new coordinate system in multispectral space where the data can be uncorrelated, i.e., the off-diagonal covariance matrix terms will approach zero. An illustration is shown in figure 2.4, from Richards (1986).

**Figure 2.4: Example of New Coordinate System Result**

The procedure is to find the vectors representing the pixel points as \( y \) in the new coordinate system by a linear transformation \( G \) of the original coordinates \( x \):

\[
y = Gx
\]
The transformation $G$ is found to make the covariance matrix in $y$ coordinates be diagonal. The following sequence of equations remaps the covariance matrix in $y$ coordinates in terms of the covariance matrix in $x$ coordinates and the linear transform $G$.

\[ \Sigma_y = E\{(y - m_y)(y - m_y)'\} \quad (8a) \]
\[ m_y = E\{y\} = E\{Gx\} = GE\{x\} = Gm_x \quad (8b) \]
\[ \Sigma_y = E\{(Gx - Gm_y)(Gx - Gm_y)'\} \quad (8c) \]
\[ \Sigma_y = G E\{(x - m_x)(x - m_x)'\} G' \quad (8d) \]
\[ \Sigma_y = G \Sigma_x G' \quad (8e) \]

The $m_y$ variables are equivalent to the $m_x$ variables in the $y$ space. Recall that $\Sigma_y$ is defined to be diagonal, and therefore $G$ may be considered to be the transposed matrix of the eigenvectors of $\Sigma_x$ as long as $G$ is orthogonal. In other words, $\Sigma_y$ is a matrix whose diagonal elements are the eigenvalues of $\Sigma_x$. As a diagonal covariance matrix, $\Sigma_y$ has elements which are the variances of the pixel data in the transformed coordinates. These variances are arranged in decreasing value along the diagonal, which means that the most variance is accounted for by $y_1$, the next most by $y_2$ and so on.

The first step in PCA is the determination of the eigenvalues of the covariance matrix. This is done by solving the following equation for $\lambda$

\[ |\Sigma_x - \lambda I| = 0 \quad (9) \]

where $I$ is the identity matrix. The transformation matrix $G$ is the transpose of the matrix of eigenvectors of $\Sigma_x$. Applying this matrix to the multispectral image data will yield the PCA transform of that data.
The PCA operation is of great use in archeological imaging, as mentioned in 2.2. Several benefits arise by transforming the bands into a space ordered by variance of the data. One is that the first few PC components tend to convey the 'important aspects' of the image, as shown by the Mayan murals, discussed in 2.2.2. The reproduction of the murals with these new images exhibits brighter colors and more distinct figures.

The other major benefit arising from PCA is more obvious in the application described by this paper. The goal is to extract hidden text and hopefully to obscure what remains. Obviously the more visible elements in the multispectral images will account for most of the variance in the image and hence be present in the first few principal components. However, the hidden text does create some variance in the images, and as such there should usually be a component which describes this variance by showing mainly the hidden text. The use of PCA to this end has also been shown by Easton, et al. (1995). However, the main drawback to the PCA algorithm is that it is 'unsupervised', i.e. no a priori knowledge about the scene is used in finding the hidden elements. In short, PCA does not utilize all available information. The next algorithm describes a more focused approach to extracting elements of an image which does use some a priori knowledge.

2.4: Orthogonal Subspace Projection

Orthogonal subspace projection, or OSP, was described by Harsanyi et al. (1994). The OSP algorithm is fundamentally different from PCA because it includes 'undesired' signatures within its formulation. This aspect is vital for use in certain archeological applications where only particular object classes are desired.
Harsanyi, et al. (1994) describes OSP as the projection of each pixel vector onto a subspace which is orthogonal to the undesired signatures. He states that the drawback associated with statistical classifiers such as PCA is that they do not account for 'mixed' pixels, which contain more than one type of material. This problem is typical in remote sensing applications where projection of a sample pixel on the ground may be 1 meter square. It is easy to imagine that such an area may contain more than one type of material. However, mixed pixels are also found in archeological imaging.

Verbally, the OSP algorithm has two steps. The first is to find the matrix operator that eliminates the undesired signatures. This operator is an interference rejection process that is optimal in the least squares sense. The second step is to calculate a vector operator that maximizes the signal-to-noise-ratio (SNR) of the desired signature. At this point, the problem of finding the desired signature is much easier because it is reduced to finding an unknown constant in white noise.

In mathematical terms, a mixed pixel $r(x,y)$ is described by the following equation

$$ r(x,y) = M\alpha(x,y) + n(x,y) $$

(10)

The variables of equation 10 are described by table 1.

Table 1: Description of Variables in Equation (10)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x,y$</td>
<td>Spatial variables defining location of pixel $r$</td>
</tr>
<tr>
<td>$r$</td>
<td>Mixed pixel vector of size $L \times 1$</td>
</tr>
<tr>
<td>$L$</td>
<td>Number of spectral bands</td>
</tr>
<tr>
<td>$M=(u_1...u_{p-1},d)$</td>
<td>$L \times p$ matrix of $p$ spectral signatures $u_i$ and $d$ the desired signature</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$p \times 1$ vector of abundances of $p$ signatures present in $r$</td>
</tr>
<tr>
<td>$n$</td>
<td>$L \times 1$ vector of random noise added to pixel $r$</td>
</tr>
</tbody>
</table>
The noise is assumed to be independent of the signal and have Gaussian distribution with zero mean. Equation (10) can be rewritten without the spatial coordinates (for brevity) after separating the desired signal \( d \) from \( M \)

\[
r = d \alpha_p + U \gamma + n
\]

where \( \alpha_p \) is the abundance of desired signature \( d \) in pixel \( r \), and \( \gamma \) is a vector containing the remaining elements of \( \alpha \).

Harsanyi, et al. (1994) describes the first step of the OSP as the elimination of the effects of the other signatures, which are the columns of \( U \). To do this, the pixel \( r \) is projected onto a subspace that is orthogonal to these other signatures in the columns of \( U \). This is done with the following \( L \times 1 \) operator

\[
P = (I - UU^*)
\]

where \( U^* \) is the Moore-Penrose pseudoinverse of \( U \). Multiplying \( U \) by \( P \) reduces the contribution of \( U \) to zero. Hence, the new equation looks like

\[
Pr = Pd \alpha_p + Pn
\]

The next step in this process is to maximize the SNR with the operator \( x^T \) of size \( L \times 1 \). Adding this to equation (13) yields

\[
x^T Pr = x^T Pd \alpha_p + x^T Pn
\]

Harsanyi, et al. (1994) derives the signal-to-noise-energy ratio by

\[
\lambda = \frac{x^T Pd \alpha_p^T d^T P^T x}{x^T P E[nn^T]P^T x} = \frac{\alpha_p^2}{\sigma^2} \frac{x^T Pd d^T x}{x^T P P^T x}
\]

The following eigenvector equation is solved to maximize the SNR,

\[
Pd \lambda^T P^T x = \lambda P P^T x
\]
with solution
\[ \mathbf{x}^T = k \mathbf{d}^T \] (17)
where \( k \) is an arbitrary scalar. This result means that the operator that maximizes the SNR is simply the transpose of the spectral signature of the object of interest.

The result from this derivation is the classification operator \( \mathbf{q}^T \)
\[ \mathbf{q}^T = \mathbf{d}^T \mathbf{P} \] (18)
This neat result first uses the \( \mathbf{P} \) matrix to eliminate the unwanted signatures in the pixel, followed by a matched filter for the desired signature to maximize the SNR. The result of this operator is a scalar weighted for each pixel that represents the abundance of the desired signature. The multi-band image becomes a single ‘fraction map’, where large pixel gray values indicate a large presence of the desired signal, while small pixel gray values indicate a small presence of the desired signal.

The OSP method has some clear advantages over PCA. It is able to apply knowledge about the scene to the extraction of the desired signature from the noise of the system and from the interference of the other signatures. It is also easier to compute than PCA. Instead of finding covariance matrices and an optimal linear transform between spaces which results in as many images as there are spectral bands, OSP does an easy computation on the matrix of undesired signatures, takes the transpose of the desired signature, multiplies them together, and applies the resulting operator on each pixel.
Chapter 3: Experimental and Testing of Algorithms

This chapter is divided into two parts. The first will discuss the actual imaging of the Archimedes Palimpsest, including descriptions of the instrumentation, the leaves imaged, the procedure, and the subsequent registration of the images. The second part will consider the multispectral image processing that was performed. The original PCA and OSP methods used will be reviewed, and then the tests on these methods will be described.

3.1: Imaging of the Archimedes Palimpsest

3.1.1: Instrumentation

Several elements were used to image the document, the illuminants, the camera, the filters and the LCTF, and the software to control the camera. These will be the focus of this section.

The scientific digital camera used was made by Photometrics, which is now owned by Roper Scientific. Photometrics provided a Sensys® digital camera with 1536 x 1024, 12 bits per pixel, enhanced blue sensitivity, a luminous coating that provides extended UV response, few pixel defects, low noise, and a built in filter wheel with 8 filter slots. The CCD characteristics are summarized in table 1, while the camera gain characteristics are summarized in table 2.
Table 1: CCD Characteristics

<table>
<thead>
<tr>
<th>CCD Type</th>
<th>KAF1602E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>1 (no pixel defects)</td>
</tr>
<tr>
<td>Coating</td>
<td>Metachrome II™</td>
</tr>
</tbody>
</table>

Table 2: Camera Characteristics

<table>
<thead>
<tr>
<th>Nominal Gain</th>
<th>Measured Gain (electrons/ADU)</th>
<th>Noise (electrons/RMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45.7</td>
<td>26.7</td>
</tr>
<tr>
<td>2</td>
<td>22.3</td>
<td>21.2</td>
</tr>
<tr>
<td>3</td>
<td>5.7</td>
<td>16.4</td>
</tr>
</tbody>
</table>

The gain measurements were made at a readout speed of 1 MHz. Additional camera parameters include a measured dark current of 2.99 electrons/pixel/second at a CCD temperature of 10° C, a camera linearity error of 0.07%.

Figure 3.1 shows the absolute quantum efficiency of a Blue Plus™ CCD sensor.
While figure 3.1 does not show the sensitivity in the near UV, it does show the increase in blue sensitivity. At 400 nm, a typical CCD has almost zero QE, while that of a Blue Plus™ sensor is approximately 30%.

The software package V, from Digital Optics was used to control the camera. This software is fully integrated with all Roper Scientific cameras. This software was used mainly to capture images and view their histograms, although it also includes other imaging tools. V also includes the scripting language ‘Vpascal’, which was used to control the camera for imaging sequences with the glass and liquid crystal filters.
Glass filters were used to restrict the passbands when acquiring some of the multispectral data. The standard astronomical photometric filters were used, with transmittances as shown in figure 3.2. In addition to these, a clear filter was used that passed all visible wavelengths while maintaining the same focal distance. All filters were and one inch in diameter.

**Figure 3.2: Filter Spectral Transmittances**

![Glass Filter Spectral Transmittances](image)

The maximum transmittance of the blue and UV filters is quite low. This fact, combined with the low QE of the CCD at these wavelengths, requires lengthening of these exposures.
The liquid-crystal tunable filter (LCTF) was also used. As stated in chapter 2, the LCTF allows the central wavelength of the passband to be varied. The LCTF was used to image the expected variations in spectral reflectances of the Archimedes text. While the glass filters allow for more spectral resolution than a traditional camera, it was not known at the time if this would be sufficient for segmentation. The availability of an LCTF would hopefully answer this query by providing a greater number of bands in the visible region.

The LCTF chosen for the project was a Varispec™ tunable filter from CRI. The Varispec had a 10nm passband, which provided significantly higher spectral resolution than afforded by the glass filters. This passband could be tuned to any integer wavelength (in nm) from 400 to 720 nm. Figure 3.3 shows the response of a filter with $\Delta \lambda = 20$nm at several wavelengths.
Clearly the filter exhibits low transmittance in the blue region of the visible spectrum.

This is similar to the glass filter problem, and the solution was the same: lengthen these exposures. Additional characteristics about the filter are shown in table 3.
Table 3: Varispec Filter Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear Aperture</td>
<td>18mm</td>
</tr>
<tr>
<td>Maximum Power Input</td>
<td>500 mW/cm²</td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>400-720nm</td>
</tr>
<tr>
<td>Angle of Acceptance</td>
<td>+/- 5° from normal</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10nm nominal at 500nm</td>
</tr>
<tr>
<td>Transmittance</td>
<td>&gt; 20% at 500 nm, for polarized input light</td>
</tr>
<tr>
<td>Leakage</td>
<td>&lt; 1 x 10⁻⁴, average</td>
</tr>
<tr>
<td>Wavelength Accuracy</td>
<td>bandwidth(λ)/8</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>storage= 0-55° C, operating= 20-45° C</td>
</tr>
<tr>
<td>Response Time (25° C)</td>
<td>40 milliseconds</td>
</tr>
</tbody>
</table>

The 18mm aperture size caused serious vignetting in images captured with the LCTF in place, but this was solved by taking multiple images and blending them together as will be discussed in sections 3.1.3 and 3.1.4.

The Varispec™ filter is controlled by electronics that accept input from a standard PC serial port. The filter is controlled by simple one- or two-letter commands. These commands were written into a script which will be detailed in section 3.1.3.

The final part of the setup is the illumination. Three different illuminants were used: tungsten, longwave UV and shortwave UV. The tungsten illumination was provided by four 40 watt photoflood bulbs. The longwave UV illumination came from
two Blak-Ray® hand-held lamps which were actually supported by specially designed lamp holders angled at 30 degrees. The shortwave UV illumination was also from two Blak-Ray® hand held-lamps in the same holders. The longwave UV lamps had peak outputs at 365 nm while the shortwave UV lamps peaks were at 254 nm.

The camera setup, complete with LCTF, looked like figure 3.4

Figure 3.4: Camera Setup

The setup from a wider perspective is shown in looked like figure 3.5
Figure 3.5: Imaging Setup

Figure 3.5 shows the copy stand used, the position of the tungsten illuminants, and the imaging devices connected to the laptop computer.

Figure 3.6 shows a leaf of parchment on the copy stand with quartz glass placed on top. The glass was used to flatten the parchment, and since quartz is transmissive in both the visible and near UV regions, it didn’t hinder the imaging.
3.1.2: The Imaged Leaves

As mentioned in chapter 2, the Archimedes Palimpsest consists of 177 leaves of parchment. The project described by this paper involved imaging 5 of those leaves. The leaves are identified by page number within the Euchologion, and their sides are denoted by ‘recto’ and ‘verso’, meaning ‘front’ and ‘back’. Each page of the Palimpsest is approximately 215 x 150mm in size. The 5 leaves which were imaged were 28, 48, 70, 80, and 81. These leaves will be briefly described in this section, and images will be shown in chapter 4.
Page 28 is from the treatise, 'On Floating Bodies'. Leaf 28R (recto) is a typical palimpsest page consisting of obvious Euchologion text and fainter Archimedes text. The other side, 28V (verso), is similar, but contains a diagram which can be seen under UV illumination. Leaves 48, from 'Method of Mechanical Theorems', and 70, from 'On Floating Bodies', are also typical palimpsest pages. However, leaf 48R does have part of another interesting diagram which is at the very edge of a page. Leaf 80 is a 'non-Archimedes' page, meaning that there is no obvious Archimedes text. This leaf was chosen to see if any processing could verify this or show it to be otherwise. Leaf 81, from 'Equilibrium of Planes', is perhaps the most challenging of the 5. 81R contains a forgery in the form of an 'illumination', or pictorial scene from the Bible. This forgery was painted in the 1930's in an attempt to enhance the value of the book and consists of paints and gold leaf. Unfortunately for the scholars, the forger scraped both Euchologion and Archimedes texts off of not only 81R but also 81V. This means that 81 is an even greater challenge than the other leaves because the Archimedes text has been scraped off twice, and on one side painted over.

3.1.3: Procedure

During the month of May, 2000 from the to the , a team of scientists consisting of Charles Dickinson, Roger Easton, Keith Knox, Lichao Wei, and Robert Johnson went to the Walters Art Gallery to image these five leaves of the Archimedes Palimpsest. This section will discuss how these leaves were imaged.

Before the actual image data acquisition could begin, it was first necessary to determine the camera exposures and apertures appropriate for each glass filter and LCTF
passband. This was done from images of leaf 48R under the various filter/illuminant combinations. The exposures were varied with fixed apertures until the histogram was spread over most of the 4095 gray levels without saturation. These exposure values were then recorded and used in the subsequent image sequences.

Each image sequence was focused with the aperture fully open, at f/2.8. This gives the camera the smallest depth of field. The focusing for tungsten illumination was performed with the green filter. The green filter was selected for the tungsten focusing because of its central position in the visible spectrum thus minimizing the effect of chromatic aberration. The UV illumination sequences were focused with the blue filter. The blue filter was used for the UV focusing because the UV light is obviously very blue, and the blue filtered images showed the greatest amount of visual clarity.

The imaging sequences were scripted using the Vpascal language. These scripts were written to automatethe filter changes and exposures. This made each sequence very time efficient. The LCTF imaging scripts were somewhat different from the glass filter scripts, as they contained the commands which opened communications with the LCTF and the control commands. Both scripts created a log file upon execution that contained the date, time, and the exposure lengths for each filter or passband. The LCTF script also included feedback from the Varispec electronic controller to verify that the correct wavelength had been set for each exposure.

It is important to note that the glass filter was used in conjunction with the LCTF to eliminate the small transmission peak at the ‘first harmonic’, or at 2λ. For example, there would be some transmission around 1000 nm for a LCTF setting of 500 nm. Therefore, the blue filter was used in the blue LCTF exposures, the green filter in the
green region, and the red filter in the red region. Obviously it would have been easier to have used a single IR blocking filter, but none was available. As the filter curves showed, the transmission of each glass filter decreases away from their centers. To reduce this effect, there was some overlap between the glass filters used. The blue filter was used from 400 nm to 500 nm, the green was used from 490 nm to 610 nm, and the red was used from 550 nm to 700 nm. This ensured that there would be less information loss. It also had the effect of producing more bands: a total of 40. While it is clear that many of these bands would be redundant, there was the possibility that some information could reside in these overlap bands that would be helpful.

All leaves were imaged in two sections. The main reason was to increase the spatial resolution. Each leaf was 6 x 8 inches, and the camera has 1536 x 1024 pixels, so the resulting resolution of the half leaf images was about 250 pixels/inch. It was thought to be sufficient. The other reason for imaging the leaves in two sections was to overcome the vignetting of the LCTF. The small aperture of the LCTF resulted in the edges of the CCD not getting any light. By overlapping the halves, this was overcome in the text region.

Additional imaging sequences were performed that captured both flat fields and MacBeth Color Checker charts. The flats were captured after every illuminant change. This step was particularly important for the short and long wavelength UV sequences because the lighting position was slightly different each time. The MacBeth Color Checker charts were acquired to help reproduce the color of the leaves. Additionally, dark frames were taken for every leaf side. The multiple dark frames ensured that the dark current correction would account for some of the noise variation.
Some conservation issues affected the imaging. One factor of concern was the tungsten illumination. While not inherently damaging to the parchment (as say, x-rays would be), the tungsten flood lamps emit a great deal of heat, that is dangerous to old parchment. Therefore, a special thermometer designed for observing the temperature of documents was used. After prolonged exposure to the tungsten, the temperature of the parchment tended to rise several degrees above the room temperature. To help alleviate this, the lights were switched off as soon as possible after imaging, and the documents were often allowed some time to cool. Also, as shown in 3.1.1, a UV transmissive quartz plate was placed on top of the parchment. This was used to flatten the parchment and reduce heat-induced cockling while allowing it to be illuminated by the UV lamps (glass blocks UV).

Another concern was potential damage from the UV lamps, particularly at 254nm (being of higher frequency and therefore energy). Unlike tungsten lamps, UV lamps are inherently damaging to parchment because they emit sufficient energy to excite electrons to different energy states. A certain number of these electrons are actually freed from the atoms, changing the chemical nature of the parchment molecules. Clearly this may damage the document.

All images and sequence logs were written to CD-ROM using a portable CD-RW. The data and logs were first collected on the portable computer controlling the imaging system, transferred to a portable hard disk and then to another computer that controlled the CD-writer. The images were saved in TIFF format and were identified by their filename which was a number whose significance was recorded in a separate log. The sequence logs were saved as simple text files.
3.1.4: Registration

Once the data had been recorded and examined, it became clear that the images in the various colors were not registered. This was very obvious when one tried to create a pseudo-natural color image by assembling the R, V, and B filtered images. There are several possible causes for this misalignment. The most severe problem was the shifting of the document that occurs when changing the illuminants. Although no movement was perceivable, it is still very likely that the document shifted when the UV lamps were placed. This would account for the registration issues between illuminant sequences.

There also were problems within the sequences. A possible reason for the inter-sequence problem was the glass filters themselves. The filters were held in the camera with tightened rubber 'o' rings, and it is entirely plausible that these rings did not hold the filters perfectly. Any tilt in the filters would cause light from certain parts of the image to be refracted differently than from other parts. An additional problem may have been due to variations of filter thickness. Again, this would cause differing amounts of refraction.

A final reason for the registration issue is due to the chromatic aberration of the lens. This would cause light passing through each filter to be focused more or less compared to the other filters.

Regardless of the cause, it became clear that the registration problem had to be solved. Any kind of spectral analysis looks down the z-axis of the image cube. If the images are not registered, then a z-axis profile will have components from other parts of the image, creating totally false spectra which are spatially dependent. Initially, a very rudimentary translating procedure was performed in Adobe Photoshop, which only
allows for integer movements of the entire image. This was not sufficient because the image would register in certain parts of the image and not in others. This suggests that there was more than just a linear shift occurring, and that other factors such as rotation or expansion might be involved.

The final registration was performed at Xerox by Keith Knox and Lichao Wei using a custom program that could shift, rotate, and expand/contract an image. An additional program was written that simply allowed the user to blink back and forth between the images in question. This was essential to properly register the images because many of the alignments were so subtle that the human eye was the best tool for seeing them. An additional program was written to automate the registration. This was done with anchor points that the computer would try to align. However, the performance was noticeably worse than hand registration method. All the results presented in chapter 4 have been registered by hand.

3.2: Testing of Algorithms

3.2.1: Software

Before discussing the algorithms used to process the Archimedes leaves, the software that implemented these algorithms must first be mentioned. The data from the leaves was clearly multispectral, and previous work by Easton, et al. (1995) had used the remote sensing software ERDAS. Therefore it was decided to use ENVI 4.0 (RSI 1998). ENVI is a very powerful tool for manipulating multispectral and hyperspectral data. The program is written in Interactive Data Language™ (IDL) (RSI 1998), which offers additional benefits such as exporting and importing data to IDL variables.
One of the most simple advantages to using ENVI for this project is its ability to create new multispectral files. The original data from the camera is in separate files. ENVI facilitates assembling these files into a single multispectral image. ENVI also includes a routine to perform PCA and OSP algorithms. This made it possible to spend more time working with the parameters of these algorithms rather than writing the algorithms themselves.

3.2.2: Original Parameters

The PCA algorithm attempted to separate the Archimedes text from the Euchologion and the parchment, based on previous success with older Palimpsest images. Initially, the PCA was performed mainly on the LCTF series images because it was thought that the larger number of bands would yield a principal component that would separate the Archimedes text. The original PCA trials simply ran the algorithm over the entire image, but yielded less than satisfactory results. The reason was found to be the centimeter guide rules that were used at the borders of the parchment and that accounted for a significant part of the image data. Because the PCA is based on the statistics of the covariance matrix, these alternating squares had a large effect on the resulting principal components. Therefore, the PCA was changed to include only the regions where text (either Euchologion or Archimedes) was present. It was this realization that led to the alteration of the size parameter in the testing phase, as described in 3.2.3.

The improved PCA results still did not sufficiently separate the Archimedes text. At this point, the problem was discussed with the DIRS (Digital Imaging and Remote Sensing) group at RIT. Their suggestion was to use OSP, which is a more directed algorithm. The original tests of the OSP algorithm were on the entire half-leaf (excluding
the centimeter rules). Like the original PCA trials, the results were not satisfactory.

However, because of the previous benefit of removing the centimeter rules from the image processing, it was realized that the OSP would also have large spatial dependencies, due to the variations in both the parchment and the text over the leaves. A good example of this is due to mold. Mold patches on the image affect the spectra, but the mold isn’t at all parts of the image. However, if the OSP is run on the entire image, it will be affected by that difference in the spectra and may not classify the texts in the mold regions as well as if it had been trained on the moldy text.

At this stage in the experimentation, it became apparent that the registration issue was worse than originally thought. The program, mentioned in 3.1.1, that used visual comparisons to register the images was being implemented. Due to the complexity and tediousness of this task, only the glass filter sets were being registered together. Not only were the sets registered within illuminants, they were also registered between illuminants. This created a 15-band multispectral image consisting of 5 bands per illuminant, tungsten, long wave UV, and short wave UV. These 15 band multispectral images that were used for the OSP algorithm.

The original image subsection used to process with the OSP was 400 x 400 pixels in the following arrangement.
The effective processing area was 1200 x 800 pixels, which covered the Archimedes and Euchologion text regions quite well. The 400 x 400 region was selected for the simple fact that the default ENVI window is 400 x 400, and the OSP worked well for this size. The OSP procedure in ENVI is quite simple. First, the region of interest (ROI) tool is used to select the training classes: Archimedes text, Euchologion text, and parchment. At least 200 pixels of each class were selected with the ROI tool. The OSP algorithm was then run on the 400 x 400 block of interest and it took the three classes as input. The result was a three-band image where each band represents the ‘fraction map’ of each class, which is a term that refers to the fact that the OSP results in an image where each pixel represents the fraction of the desired signature that is present at that spatial location.

It should be mentioned that the results to be shown in chapter 4 do not result from the 15-band image cubes. While the OSP results from the 15 band images were satisfactory, they did contain some undesirable noise. Inspection of the short-wave UV images reveals them to be quite noisy. This is shown in figure 3.8.
These short-wave UV images were removed from the data cube, and the OSP was run again. Fortunately, the information contained in these images was not significant as the results were just as good as the 15-band image results. Therefore, all subsequent processing on the leaves was performed on the 10-band images consisting of tungsten plus long-wave UV filter sets.

3.2.3: Testing

After the original image processing, it became of interest to examine some of the parameters used in the PCA and OSP algorithms. The original processing revealed that the OSP in 400 x 400 blocks yielded the most satisfactory results compared to the PCA and the OSP on the entire image. As such, it was decided that all of the tests performed on both PCA and OSP would be compared to the 400 x 400 OSP. Additionally, only one leaf was used in the comparisons. Leaf 48R, left side was chosen because it is a fairly typical example of the condition of the Palimpsest.
The first parameter to examine was the size that the algorithms were used on. With the PCA it became apparent that a smaller size that excluded the centimeter rules was beneficial, and the OSP algorithm was greatly improved by processing the leaves in 400 x 400 blocks. If reducing the processing size was so beneficial, what would happen if the size was further reduced? A similar question is what if the 400 x 400 is too small? Based on these queries, both PCA and OSP algorithms were performed in 200 x 200, 400 x 400, and 600 x 600 blocks, and compared to the 400 x 400 block OSP.

All tests were run on the same overall region as the 400 x 400 block OSP. This was simple for the 200 x 200 blocks as each 400 x 400 block included four such blocks. However, the 600 x 600 blocks were slightly more complicated. These images covered the same area, but with significant overlap in the y dimension (600 is an integer multiple of the total number of x pixels, 1200). To solve this, a program was written which linearly blends the overlap region. Therefore, at the top edge of the overlap, the pixels are entirely from the top image, in the middle they are a combination of 50% top and 50% bottom, and at the bottom they are only made of the bottom image.

To compare the images to the standard, the 200 and 400 square blocks and the top-bottom blended blocks were stitched together. This was straightforward for the OSP results because they all included an Archimedes band. However, the PCA results had no such distinct result; they had 10 principal components. To create the stitched PCA images, the component which best extracted the Archimedes text was visually chosen. In some cases the component had to be inverted to match the OSP standard scheme of white text and black background. Many PCA blocks results had no obvious ‘Archimedes bands’, in which case a component was chosen which contained no Euchologion text
either. By doing this, the stitched PCA images would not have areas where the Euchologion text would draw one’s attention from the Archimedes text.

Another factor of interest was the bit-depth of the images. As mentioned in section 3.1.1, the Sensys camera generates 12 bits/pixel image data. However, another team working on the Palimpsest used a camera with 8 bits/pixel of image data, but had a larger CCD (3k by 2k pixels). Therefore, it was necessary to decide if the extra 4 bits/pixel of resolution was needed, or would it be possible to sacrifice the intensity resolution for spatial resolution. To make the comparison, the original 12-bit images were saved as 8-bit images, and the 400 x 400 block OSP was used.

In addition to lacking the 12 bits/pixel, the other teams’ camera only acquired 3-band RGB images for the two illuminants used, tungsten and long wave UV. To verify that the additional bands were necessary, comparisons were made of both 6 band (BVR) and 8 band (CBVR) results to the original 10 band OSP result. Again, these were processed with the 400 x 400 blocks.

All of the comparisons just listed were compared visually with the help of some difference images. In the remote sensing, algorithms often are tested by testing how much they resemble ‘ground truth’, or a map which states what a pixel on the ground actually is. Unfortunately, it is not possible to obtain any kind of ground truth for an ancient document such as the Archimedes Palimpsest. Between the damage done to the parchment and the overwritten characters, it would be very difficult to accurately assess the composition of any single pixel, in addition to the fact that the pixel size would be far too small to observe visually. Because the end result of this project is a set of images to be translated by a scholar, the lack of a ground truth is not overly important. What is
important is how the results look visually, because the scholar will be using his vision to decipher the text. Therefore, the results from the algorithm tests will all be compared visually in chapter 4. Difference images were created to help this comparison. The difference images were calculated by subtracting each image from the 10-band 400 x 400 block OSP ‘standard’, and squaring the result to produce an image where large gray values indicate a relatively large amount of change dark pixels indicate little change. These difference images allow one to visually ‘zoom in’ on areas where there has been a big change, and see if it is for better or worse.

It is important to note that some modifications had to be made to create a difference-squared image for the PCA algorithm used in the size parameter experiment. The reason for this is that while the OSP results in a fraction map, the PCA algorithm does not. Therefore, it becomes difficult to compare these two images with a simple difference-squared method. To solve this problem, both the standard 400x400 OSP image and the PCA images were normalized from zero to one before applying the difference squared method. While this removes some information from the resulting image, it still allows the difference image to be used to highlight regions of large differences.
Chapter 4: Results

This chapter discusses the data collected from the Archimedes Palimpsest and the testing performed on the algorithms used on this data. Section 4.1 will show images of the leaves which were imaged at the Walters Art Gallery. This section will include both color images of the leaves taken under tungsten illumination, thus giving a visual impression of the leaves, as well as images taken with long wave UV illumination which will show the underlying text. Section 4.2 contains the original processed images of the leaves, while section 4.3 will show the results of the experiments performed on the PCA and OSP algorithms.

4.1: Images of Leaves

4.1.1: Leaf 28

Figures 4.1 and 4.2 show the color and blue filtered UV images of leaf 28R.
Figure 4.1: Color Image of 28R
Leaf 28R is a typical example of the condition of the Palimpsest. There are two very large mold spots, and the Archimedes text becomes quite apparent under the UV
illumination. Figures 4.3 and 4.4 show the other side, 28V, in color and blue filtered longwave UV.
Figure 4.3: Color Image of 28V
There are several features to note about 28V. The first is that the same mold spots in 28R actually go through the parchment to this side. Attention should also be called to the
diagram which can be seen on the bottom half of 28V, indicated by the red arrow. This is the only full diagram that can be seen in the 5 leaves imaged.

4.1.2: Leaf 48

This sub-section will be slightly longer than the rest because leaf 48R was chosen for the testing of the algorithms, so all of the glass filter images will be shown. Figure 4.5 is the color image of 48R.
One of the most obvious features of 48R is the large mold spot on the left side. This is a difficult area to process because the mold complicates the spectral signatures of the Archimedes text. Another unique feature of this leaf is the text which is not made of the
typical iron gall ink. This ‘rubric’ can be seen as the slightly larger, redder characters in the third and fourth lines from the bottom of figure 4.5. This rubric text has a different spectral character than the Euchologion.

Figure 4.6 is the blue filtered long wave UV image of 48R.
The typical enhancement of contrast of both the Euchologion and Archimedes texts as compared to the parchment is apparent. This is true even in the large mold spot.
The following sequence of images, 4.7 through 4.11, are the glass filter set for leaf 48RL illuminated with a tungsten source.

**Figure 4.7: Clear Filtered Tungsten 48RL Image**
Figure 4.8: Blue Filtered Tungsten 48RL Image
Figure 4.9: Green Filtered Tungsten 48RL Image
Figure 4.10: Red Filtered Tungsten 48RL Image
It is interesting to note the effect of the filtering in the images. The Archimedes text is more apparent in the green and especially in the blue filtered images, but is almost totally absent in the red and IR images. This indicates that its spectral signature is slightly higher in the blue than in the red. Another interesting feature is that the mold spot is very visible in the blue, green, and red images, but is much less distinct in the clear and IR images. Because of the violet color of the mold, it can be expected that it will show up in the blue, green and red images, but the IR is obviously able to see through the mold quite well.

Figures 4.12 through 4.16 contain the glass filtered set of long wave UV illuminated images of 48RL.
Figure 4.12: Clear Filtered LWUV 48RL Image
Figure 4.13: Blue Filtered LWUV 48RL Image
Figure 4.14: Green Filtered LWUV 48RL Image
Figure 4.15: Red Filtered LWUV 48RL Image
The IR filtered image is able to see through the mold, which is so enhanced in both the green and red images. However, the mold is much less obvious in the blue image, unlike the tungsten illuminated blue image. It is also interesting to see the stains on the parchment which the green and red images enhance.

Figures 4.17 and 4.18 contain the color and blue filtered long wave UV images of 48V.
The most notable feature is simply that the mold found on 48R is also on 48V.
4.1.3: Leaf 70

Figures 4.19 and 4.20 show leaf 70R as a color and blue filtered long wave UV image.
Leaf 70R has a large tear in the lower right corner, but is otherwise much like leaves 28 or 48. Figures 4.21 and 4.22 show images of leaf 70V in color and UV.
Figure 4.21: Color Image of 70V
The rubric text seen on 48R can again be seen in figure 4.20 in the first few lines.
4.1.4: Leaf 80

Figures 4.22 and 4.23 are of leaf 80R.

Figure 4.22: Color Image of 80R
These images make it clear that there is probably no Archimedes text present on 80R. If any was present, the fluorescence of the parchment under UV illumination would make it somewhat visible, but this is not the case.

Figures 4.24 and 4.25 show leaf 80V.
Figure 4.24: Color Image of 80V
These images again show that leaf 80 has no distinguishable Archimedes text.
4.1.5: Leaf 81

The most difficult leaf of the 5 was leaf 81. On the recto side, there is the forged painting. Figures 4.26 and 4.27 show 81R in color and blue filtered long wave UV.
Figure 4.26: Color Image of 81R
Figure 4.27: Blue Filtered LWUV Image of 81R
These images make it clear that it is extraordinarily difficult to extract any kind of text from 81R. Even in the UV, it is very difficult to see any text at all. However, the verso side, 81V, is quite different. This side was scraped off once more when the forgery was done, but as the next two images will show, the UV illuminant can still bring the texts into view. Figures 4.28 and 4.29 show the color and blue filtered UV images of 81V.
Figure 4.28: Color Image of 81V
Figure 4.29: Blue Filtered LWUV Image of 81V
While the color image makes the characters almost indistinguishable, the enhanced contrast that the UV illumination provides makes the characters quite clear. As such, this leaf was processed, and will be shown in section 4.2.

4.2: Original Processed Images

The original 400 x 400 block OSP results will be presented here in addition to two sets of principal components. It is important to note that all of the original processed Archimedes band images were inverted for greater readability for the scholars. Also, leaf 80 and 81R were not processed. This was due to the fact that neither produced satisfactory results, either because there was no Archimedes text present (80), or it could not be seen (81R).

4.2.1: Leaf 28

Figure 4.28 and 4.29 are the OSP processed images of 28R and 28V.
It can be seen that the OSP has done a good job suppressing the Euchologion and highlighting the Archimedes text. The diagram on leaf 28V was a particularly exciting result because it is almost impossible to see with the human eye.

4.2.2: Leaf 48

Figures 4.30 and 4.31 show processed images of 48R and 48V.
Figure 4.30: OSP Processed 48R
Figure 4.31: OSP Processed 48V

It is again interesting to note the diagram indicated by the red arrow in figure 4.30. Much like 28V, this diagram is almost invisible to the naked eye.

This section also includes images of the original PCA processing of 48R, the right half, as well as the other two OSP bands (Euchologion and parchment) for 48V. Figure 4.32 shows the 16th principal component of the right side of 48R, the LCTF series.
This image, compared to figure 4.30, shows how much better the OSP algorithm works compared to PCA. Many characters are missing, and the leftmost line is obscured by a large black spot. Also, the rubric text, indicated by the red circle, interferes with the legibility of the Archimedes text.

It is also of interest at this point to show a set of principal components of 48RL. This PCA set comes from the 10 band glass filter images. The PCA was performed on a section of 48RL containing all of the text, but excluding the parchment edges and the black and white scales. Figures 4.33a through 4.33j show the large section principal components.
This 1st component looks much like a longwave UV image. The Archimedes text is visible and the mold spot at the top is very obvious, much like the green filtered UV band. Being the 1st component, this image should exhibit the most variance. Because the Euchologion and Archimedes texts cause the most variance in the image (light parchment to dark text), they are the major feature of this image.
The 2nd component image still has Euchologion as a major feature, but there are also features related to the parchment which begin to show up. The large black spot in the center of the image with the adjacent light spot in the lower right corner are very visible. This suggests that the changes in the parchment over the leaf are a significant source of variance.
The 3rd component is the first in which the Archimedes text begins to be more visible than the Euchologion. This is particularly obvious on the left half of the image. However, the image is clearly made up of many other features as well, including more Euchologion and parchment variations.
Figure 4.33d: 4th Principal Component of 48RL

The 4th component is the only image in this series where the Euchologion is actually suppressed, while the Archimedes is not. Unfortunately, very little of the Archimedes is seen.
The 5th component does have some evidence of having a lot of Archimedes text, but in fact the text is very indistinct. Most of this component describes variations in the parchment.
Figure 4.33f: 6th Principal Component of 48RL

The 6th component is mostly composed of small variations in the image, and hence it looks quite noisy.
By the 7th component, most of the image consists of noise. However, it is interesting that Euchologion characters can still be seen. These are probably due to the minor registration issues that remain between the spectral bands.
The 8th component interestingly displays some Archimedes text. However, the text which is visible covers the same region as the Archimedes text which is shown in the 4th component. It may be that this Archimedes text is somehow different from the rest and hence it shows up in the analysis.
Figure 4.33i: 9th Principal Component of 48RL

Again, the 9th component shows some Archimedes text in the same region in addition to random noise.
The 10th component shows the misalignment between the bands like the 7th component.

Figure 4.34 shows a plot of the eigenvectors which make up the first 4 components. The eigenvectors represent how much of each band had to be added or subtracted to make up each of the principal components.
Figure 4.34: Eigenvector Plot of 48RL

Figure 4.34 shows that the 1st component is mostly made of the longwave green, red, and IR bands. This is as expected because the component looks much like a longwave image. The 3rd and 4th components, which contain distinct Archimedes text, are quite similar. The main difference is the opposite signs in the longwave clear, blue, green, and red bands. Although they differ in sign, they are almost equivalent in magnitude. Both of the components then add a large amount of longwave IR, then subtract small amounts of the tungsten bands.

Figure 4.35 and 4.36 show the other two OSP results from 48V. These are what the algorithm comes up with if the desired signature is Euchologion or parchment.
Figure 4.35: Euchologion OSP of 48V
Both of these results are as expected. The Euchologion band highlights the Euchologion text very well because the signal is more obvious than the Archimedes signal. The parchment band looks like a UV image because the neither texts look like the parchment signal, and thus show up dark in the fraction map, much like a UV image where the parchment fluoresces while the texts stay dark.
4.2.3: Leaf 70

Figures 4.37 and 4.38 show processed images of leaf 70.

Figure 4.37: OSP Processed 70R
Unfortunately, the OSP processing could not bring out the Archimedes text from the mold spot seen in figures 4.21 and 4.22.
4.2.4: Leaf 81

Figure 4.39 shows the processed image of 81V. Recall that this is the leaf which was totally scratched off for the forgery.

Figure 4.39: OSP Processed 81V
One of the problems with this image is the greater visibility of the Euchologion text. This means that the algorithm did not suppress the Euchologion signature as well as in the other leaves. This is to be expected because both texts were scraped off, meaning both signatures look more like the parchment signature because there is less ink on the parchment.

4.3: Algorithm Testing Results

This section will display and discuss the results obtained from the various tests done on the OSP and PCA algorithms. As all testing was performed on 48RL, this section will be split up by experiment. Section 4.3.1 will list the PCA and OSP results of varying the size parameter, 4.3.2 will show how 8 vs. 12 bits per pixel affects OSP, and 4.3.3 will show how 6 and 8 band multispectral images compare to 10. As previously mentioned in chapter 3, the images were compared to the 400x400 block OSP with 10 bands and 12 bits per pixel both visually and with the help of a difference squared image. It is important at this time to display this 'standard' image, shown in figure 4.40.
The histogram of this image is shown in figure 4.41.

**Figure 4.41: Histogram of Original 400x400 Block OSP Image**

![Histogram of 400x400 OSP Image](image)

The resulting comparisons to this image will now be presented.

**4.3.1: Size Parameter Experiment Results**

This section will show the effect of varying the size parameter for the PCA and OSP algorithms. As the standard image is a 400x400 block OSP, only the 200x200 and 600x600 block OSP images will be presented, while all three sizes will be presented for the PCA algorithm. Images 4.42 and 4.43 are the 200x200 block OSP result and its difference squared image.
Figure 4.42: 200x200 Block OSP Image
Figure 4.43: 200x200 Block OSP Difference^2 Image

Figure 4.44 is a histogram of this difference image.
The histograms of the difference images are intended to show the extent of the error from the standard image. Although it is impossible to see, a few pixels had an error as great as the square root of about 3, or around 1.7 digital counts (dc’s). This may seem insignificant until one recalls figure 4.41, the histogram of the original image. This plot shows that the dc’s of the standard image only range from approximately -3 to +3, a range of 6. Therefore, a maximum error of 1.7 is really a 28% difference from the original image, which is very significant. The converse of this argument is that the vast majority of the pixels have a difference very near zero, which is why the images look so similar. It is nevertheless important to keep in mind how big the biggest error is.
Figure 4.43 reveals several areas of interest, marked by red number. The area indicated by number 1 is some Euchologion text. This showing up in the difference image means that the two algorithm parameters suppressed the Euchologion in this region to varying degrees. Figure 4.45 shows a enlarged version of this section from both the 200x200 and standard 400x400 images.

**Figure 4.45: Enlarged Section 1 from 4.42**

This figure clearly shows that the 200x200 block OSP did not suppress the Euchologion as well as the 400x400 standard OSP. Obviously this is only a small subsection of the entire image, but the difference is noticeable to the eye and is therefore significant.

Figure 4.46 shows the enlarged region number 2.
This region shows up on the difference image as a white patch with the Euchologion characters as black, meaning that the difference between the characters is small, but the surrounding difference in parchment values is large. This is just as important as the last region. Although the actual pixel values are similar, the resulting contrast from the surround makes the Euchologion characters visible, and therefore distracting. It is also interesting to note from figure 4.46 that the Euchologion scribe lines (like rules on notebook paper) are more visible in the 200x200 OSP image. These would also be a distracting influence.

The third region of interest from figure 4.43 is the large white blob in the center of the image. This section is shown enlarged along with the same section from the standard image in figure 4.47.
This enlargement reveals the cause of this large difference. The standard 400x400 block processing has much more noise in this region. Recall figure 4.5 from the beginning of this chapter. This color image of 48R has a large moldy region on its left side where this section resides. This indicates that the 400x400 OSP does not suppress the parchment in the presence of mold as well as the 200x200 OSP does.

The 200x200 block PCA results will now be presented and discussed. Figures 4.48 and 4.49 show the image and difference squared image results from this experiment.
Figure 4.49: 200x200 Block PCA Difference^2 Image

Figure 4.50 shows the histogram to the difference squared image.
It is visually obvious from figures 4.48 and 4.49 that the PCA does a much poorer job on extracting the Archimedes text while suppressing the Euchologion and parchment than the standard OSP processing does. It is important to recall at this point that the difference squared image was generated by first normalizing the standard and PCA images. Therefore the resulting histograms information is not particularly valid, but it is presented for completeness.

Selecting regions of interest from figure 4.49, the difference image, is difficult because the PCA image is full of huge differences and because the normalization step lessens the importance of the ‘large difference’ areas. Nevertheless, it is possible to discuss some regions which typify the large differences. The first region to discuss,
indicated by the red 1, contains some Euchologion like characters, but is otherwise much like any other region from the difference image, and is shown in figure 4.51.

Figure 4.51: Enlarged Section 1 from 4.49

This is one of the many examples of the poor performance of the PCA algorithm as compared to the OSP. The Euchologion characters are much more visible in the PCA image, which is why they show up in the difference image. Also, the top half of figure 4.51 shows that many of the characters that become visible with the OSP are obliterated by the PCA because of the large amount of ‘noise’ in the form of white blobs. These blobs are most likely due to the variations in the parchment. While the OSP algorithm is actively suppressing the parchment influence, the PCA is not, so the resulting images can be expected to have more visible effects due to both the parchment and the Euchologion.

The second region of interest, shown in figure 4.52, is an example of how the PCA difference squared images can be misleading.
While the difference image does not appear to have large areas of intra-image discrepancies in this region, the enlargements of the section show that in fact the two images are very different. The section of the PCA image is an example of where there was no obvious Archimedes text component, so a component was chosen which doesn't have any Euchologion text either. Several characters are visible in the OSP image, while the PCA is basically a constant gray value.

In addition to making comparisons to the OSP algorithm, it is also interesting to compare the local block PCA processing to a PCA run on almost all of the image. Figure 4.53 shows the result of a PCA run on the region of 48RL containing all of the Archimedes and Euchologion text.
Figure 4.53: ‘Full’ Image PCA
To compare this image to the 200x200 block PCA image, the same enlargements will be used in addition to a third enlargement indicated in figure 4.49. Figure 4.54 is the first of these enlargements.

**Figure 4.54: Enlarged Section 1 from 4.49**

It is not obvious from figure 4.54 which method is performing better. Clearly neither pulls the Archimedes text out sufficiently.

Figure 4.55 displays the second enlarged comparison.
These images give more interesting information about the comparison. It appears that the full image PCA is doing a slightly better job at extracting the Archimedes text, although it extracts the Euchologion just as much. The distinction is that while the 200 block PCA in this region results in the parchment being almost the same gray value as both texts, the full image PCA results in parchment pixels which are significantly darker than the texts. The higher contrast means that the texts in this region are easier to read.

The final comparison of 200 block vs. full image PCA is shown in figure 4.56.
This region is perhaps the most dissimilar between the two methods. The 200 block PCA does an excellent job in this region of pulling out the Archimedes text while suppressing the Euchologion and the parchment. The full image PCA, on the other hand, doesn’t extract anything. Figures 4.54 and 4.55, while different, are also predominantly similar. Figure 4.56, however, shows that the two methods can result in very different images.

The comparison to be made for the 400x400 block size is obviously limited to the PCA algorithm because the standard is a 400x400 OSP image. Figure 4.57 and 4.58 show the 400 square PCA image and its difference image respectively.
Figure 4.57: 400x400 Block PCA Image
Figure 4.58: 400x400 Block PCA Difference^2 Image

Figure 4.59 is the histogram of the difference image.
While, as previously mentioned, it is difficult to assign a meaning to the PCA difference images values, it is possible to compare one PCA difference image to another in terms of magnitude. As figure 4.59 shows, the maximum difference is around 5, as compared to 2.4 from the 200 square PCA image. Visually the larger error is clear. The 400x400 block PCA image has very little Archimedes text as compared to the standard OSP image. This method suffers even more from the variations in the parchment than the 200x200 block PCA does. However, if one recalls figure 4.53, the full image PCA, the performance of the 400x400 block PCA can be viewed in a different light. Only one
region from these images will be used for inspection as it is exemplary of other portions.
This is shown in figure 4.60 and 4.61, and is indicated by the number 1 in figure 4.58.

Figure 4.60: Enlarged Section 1 from 4.58

Figure 4.61: Enlarged Section 1 from 4.58
These figures make it clear that while the standard OSP out performs the 400x400 block PCA, the 400x400 block PCA is much better than the full image PCA. There are obviously regions where both PCA methods fail to extract the Archimedes text, but in general the 400x400 PCA method extracts more than the full image PCA.

Figures 4.62 and 4.63 introduce the 600x600 block OSP blended image and difference squared image.
Figure 4.62: 600x600 Block OSP Image
Figure 4.63: 600x600 Block OSP Difference^2 Image
And figure 4.64 is the histogram of the difference image.

Figure 4.64: Histogram of 600x600 Block OSP Difference^2 Image

Figures 4.63 and 4.64 show that the 600x600 block OSP processing yielded a very similar image than the standard processing did. The largest error was only around 1.4 dc’s, and much of the difference image is black, indicating little difference.

Although the images are very similar, it is important to highlight some of their differences. Figure 4.65 shows an enlargement of the first area of interest from figure 4.63.
Both this section and section 2 are of interest because of their large white blobs in the difference image which almost look like mold. Referring back to figure 4.5, the color image of 48R, and looking in this region on the left (bottom) side of this image, it becomes clear that these sections are on the edge of a large mold spot. Looking at the enlargement in 4.65, it can be seen that the 600x600 OSP classified this blob as not Archimedes text, it is almost black. However, the standard 400x400 OSP was not as certain about this region and its value is slightly higher. This kind of effect can be seen again in figure 4.66.
Again, this area of large difference comes from the right side of each enlargement in 4.66. This spot is probably due to the moldy area also, and is more prevalent in the 400x400 block OSP standard. It is also interesting to note that the 600x600 block enlargement is less noisy, the parchment areas have lower dc’s, meaning the OSP is classifying them as ‘definitely not Archimedes text’.

The results of the 600x600 block PCA were not nearly as impressive as the 600x600 OSP results. They are shown in figures 4.67 and 4.68.
Figure 4.67: 600x600 Block PCA Image
Figure 4.68: 600x600 Block PCA Difference^2 Image
And figure 4.69 is the histogram of this difference image.

Figure 4.69: Histogram of 600x600 Block PCA Difference^2 Image

![Histogram of 600x600 Block PCA Difference^2 Image](image)

Much like the 400x400 block PCA, the 600x600 block PCA results are very disappointing. The only area where the Archimedes text is extracted is the bottom four lines, while the standard image manages to extract 16 lines of text from top to bottom of 48RL. The text that is recovered is in the presence of distracting Euchologion characters and parchment variations.

When comparing the 600x600 block PCA to the full image PCA in figure 4.53, the conclusions to be made are mixed. Clearly the whole bottom right corner of 4.53 is much worse than 4.67. However, looking at an enlargement of section 1 from 4.68 of the
standard, 600x600 PCA, and full image PCA, one can see that the full image PCA doesn’t always perform poorly. This is shown in figures 4.70 and 4.71.

Figure 4.70: Enlarged Section 1 from 4.68

Figure 4.71: Enlarged Section 1 from 4.68
Figure 4.70 reiterates the fact that the OSP again does better at extracting the Archimedes text. Figure 4.71 shows that in certain regions, the full image PCA does a much better job than the local 600x600 block method does. Not only are the Archimedes characters brighter compared to the parchment background, but the Euchologion characters are much less visible than in the 600x600 PCA result.

4.3.2: Bit Depth Parameter Results

This subsection will compare the standard 10 band 12 bit 400x400 block OSP image to both a 10 and a 6 band 8bit 400x400 block OSP images. For ease of reading, the standard image will be presented again in figure 4.72. The 8 bit, 10 band image is shown in 4.73, and the difference squared image is in 4.74.
Figure 4.72: 12 bit, 10 band, 400x400 Block OSP Result
Figure 4.73: 8 bit, 10 band, 400x400 Block OSP Result
Figure 4.74: 8 bit, 10 band, 400x400 Block OSP Difference^2 Image
And figure 4.75 is the histogram of the 8 bit 10 band difference squared image.

**Figure 4.75: Histogram of 8 bit, 10 band, 400x400 Block OSP Difference^2 Image**

Figure 4.74, the difference image, shows that there are very few observable differences between the two images. The differences which are present are not due to one method extracting the Archimedes text better or suppressing the parchment and Euchologion text more, they are small differences occurring on a pixel by pixel basis.

Figures 4.76 and 4.77 show the 8 bit, 6 band (RGB under tungsten and long wave UV) OSP result and difference squared images.
Figure 4.76: 8 bit, 6 band, 400x400 Block OSP Result
Figure 4.77: 8 bit, 6 band, 400x400 Block OSP Difference^2 Image
Figure 4.78 is the histogram of figure 4.77.

**Figure 4.78: Histogram of 8 bit, 6 band, 400x400 Block OSP Difference^2 Image**

![Histogram of 8 Bit, 6 Band Difference^2 Image]

It is clear from both the histogram and the difference squared image that going from 10 to 6 spectral bands causes significant changes. Figure 4.79 is the first example of this, corresponding to the large area of difference indicated by the number 1 in figure 4.77.
This figure shows how much better the 10 band image suppresses the parchment and the Euchologion as compared to the 6 band image. It also results in Archimedes characters which are slightly clearer, as indicated by the arrow.

Figure 4.80 is another example of the poorer performance of the 8 bit, 6 band method, corresponding to the number 2 on figure 4.77.
Figure 4.80: Enlarged Section 2 from 4.77

The visibility of the Euchologion characters is striking in the 6 band image, which is why they are so visible at the bottom of the difference image.

4.3.1: Band Number Parameter Results

The results of adjusting only the number of bands will be presented in this subsection. The 8 band image was composed of the red, green, blue, and clear filters under tungsten and longwave UV illuminants, while the 6 band image was composed of only the red, green, and blue filters under tungsten and longwave UV illuminants. Figures 4.81 and 4.82 show the OSP of an 8 band image of 48RL and its difference squared image.
Figure 4.81: 8 Band OSP Result
Figure 4.82: 8 Band OSP Difference^2 Image
Figure 4.83 is the histogram of 4.82.

**Figure 4.83: Histogram of 8 Band OSP Difference^2 Image**

The difference squared image shows that, much like the 8 bit 10 band image, there is little visual difference between the 8 band image and the 10 band standard. Again, the differences are small, and not due to one method extracting the desired text more than the other.

Figures 4.84 and 4.85 show the 6 band OSP result and its difference squared image.
Figure 4.85: 6 Band OSP Difference^2 Image

Figure 4.86 is the histogram of 4.85.
If one compares figure 4.85, the difference squared image for the 12 bit 6 band image, to figure 4.77, the difference squared image for the 8 bit 6 band image, one finds that they look almost identical. This indicates that the lack of performance is due to the number of bands, not the bit depth. The same areas will be enlarged for inspection in figures 4.87 and 4.88, and the reader is encouraged to look back at figures 4.79 and 4.80 to see how similar they are.
These enlargements show the same thing figures 4.79 and 4.80 did, that the 6 band OSP results in a reduced ability to suppress the parchment and Euchologion signals.
Chapter 5: Conclusions

This chapter formulates conclusions based on the algorithm testing, shown in section 4.3. The chapter will be split into four sections. Section 5.1 will make conclusions about adjusting the size parameter and the OSP vs. PCA comparison. Section 5.2 will discuss the 8 vs. 12 bit comparison, and section 5.3 will discuss the 6 and 8 band vs. 10 band comparison. The final section will draw elements from all of the conclusions to summarize this paper, and mention future research that can be done in this area.

5.1: Size Parameter and OSP vs. PCA Conclusions

This experiment attempted to address several questions. First, which algorithm performs better, PCA or OSP? Second, how does adjusting the size parameter affect the OSP algorithm? And the corollary to this query, how does adjusting the size parameter affect the PCA algorithm? These questions will be discussed in this section.

The first of these questions is the easiest to answer. The results of this experiment conclusively proved that for this application, the OSP algorithm is much better than the PCA algorithm. None of the size settings, 200x200, 400x400, or 600x600, showed the PCA performing better than the OSP. This is exemplified in all of the images and enlargements in chapter 4, section 4.3.1.

This conclusion is significant for several reasons. One reason is the lack of use of the OSP algorithm in any field except remote sensing. While the PCA algorithm has become popular in fields such as image processing and color science, OSP has not. It is important that the OSP algorithm be implemented more in both archeological imaging
and in other imaging related fields. Another reason is that the PCA algorithm turns out to be computationally much slower than OSP. This is probably due to the fact that PCA results in as many components as bands, while OSP only results in as many images as classes. An final reason is that the OSP algorithm is targeted on a signature of interest, and as such it comes up with a single image corresponding to that signature. PCA, on the other hand, is not targeted. Therefore, to find the hidden characters on an ancient document, it is necessary to go through every principal component to find which has extracted the characters from the background, if there is such a principal component. Eliminating this guesswork from the problem is an important benefit.

The second question, how does the size parameter affect the OSP results, is more difficult to answer. The results from this application indicate that the smaller 200x200 block OSP performed slightly worse than the 400x400 standard, while the larger 600x600 block OSP performed slightly better. The 200x200 block OSP has difficulty suppressing the Euchologion characters and their scribe lines in certain regions. However, in other regions, the 200x200 OSP actually suppresses the parchment signal better than in the 400x400 standard. The 600x600 OSP results show that they do a better job at suppressing the mold and parchment than the 400x400 standard.

While these conclusions seem to be true for the half leaf image that was used, it is not certain that they would be true for the other leaves. In truth, the adjusting the size parameter had little visual difference for the OSP algorithm. Any conclusions based on the experiments could probably be reversed by looking at different document leaves, different documents, or by having another imaging system. It is clear that more research
is needed in this field to determine how the different statistical image data generated by varying the size parameter affects the outcome of the OSP algorithm.

The final question of this section, how does the size parameter affect the PCA results, is slightly easier to answer. The results from these experiments show that in most regions, the block PCA processing is preferable to running the PCA on the entire image. This is to be expected because of the statistical nature of the PCA algorithm. It is in the nature of ancient documents to become moldy and stained. This means that there are large variations across each leaf, which causes difficulty for the PCA. The large variations will translate into statistical differences, so the new principal component axes will probably try to explain the statistical differences in these variations across the leaf. Therefore, they will not be as good at explaining the differences in the Euchologion vs. Archimedes texts. However, if one splits the leaf into segments, there is a greater chance that within the segment the parchment will be similar, so the new axes will describe the text differences better. This does not mean to say that smaller is always better. The tradeoff is that one sacrifices the data on which the PCA is ‘trained’ on, i.e. a very small region will have fewer characters for the PCA to describe. However, it can be concluded that some kind of regional PCA is preferred for processing ancient documents to a full image PCA.

5.2: 8 vs. 12 Bit Image Comparison Conclusions

The goal of the 8 vs. 12 bit comparison was to determine if the 12 bit data acquired by the scientific camera used in this project was truly necessary. The additional 4 bits of data are theoretically important, but it was unknown as to how they would affect
the OSP results. Based on the experiments performed, it can be concluded that the 12-bit image data is not significantly better than the 8-bit image data for the OSP algorithm results. The differences showing up in the difference image are diffuse and small, and the visual difference is almost non-existent. What became apparent in this and in the band number experiment was that the spectral resolution had far more to do with the OSP results than the intensity resolution. This can be seen in the 8-bit, 6 band image and in the 12-bit, 8 and 6 bit images.

The fact that only 8-bit image data is necessary for good OSP results is very significant for this application. First, this means that more traditional scientific cameras can be used for imaging ancient documents. These 8-bit cameras are generally less expensive and more readily available than 12-bit cameras. The need for only 8-bit image data is also significant because it allows a greater signal-to-noise ratio for the acquired images. Reduced noise is especially important in spectral bands where little light would be incident, such as blue wavelengths under tungsten illumination.

5.3: Band Number Parameter Conclusions

This experiment attempted to discover how the number of spectral bands captured affect the results of a three class OSP. To do this, both 6 and 8 band image OSP results were compared to the original 10 band image OSP result. Recall that the 10 band image was composed of the five filters, clear, red, green, blue, and IR, under tungsten and longwave UV illuminants. The 8 band image was the same set without the IR filter, and the 6 band image was without the IR and the clear filters. The 8 band result was found to be very similar to the 10 band result, both visually and in terms of the data. The 6 band
result was almost identical to the 8-bit, 6 band result from the previous experiment. The 6 band OSP image did not suppress the Euchologion text or the parchment as well as either the 8 or 10 band results. Therefore it can be concluded for this type of application that at least 8 bands are necessary to properly suppress undesired signatures in a three class OSP.

This conclusion is unsurprising given the OSP rule of thumb that states that the number of spectral bands must at least equal the number of classes to separate. So, for three classes, three bands are the absolute minimum. However, if one wants to properly suppress the other, undesired signatures, more bands are necessary. Given that there are only three classes, the fact that 8 band results are not significantly worse than 10 band results is not surprising either. At that point, the algorithm is probably suffering from diminishing returns.

The fact that 8 bands are necessary to suppress undesired signatures is very important for this type of application. This conclusion means that multispectral data is required for best OSP results. This is of no surprise to the remote sensing community who collect multi and hyperspectral data on a regular basis. However, most other fields, archeological imaging included, are still using traditional three color digital cameras. For two different illuminants, that means 6 spectral bands, which has been determined to be insufficient. Therefore it is vital for the archeological field to start using multispectral cameras to acquire their data. Not only does it allow for better signal processing, but it also yields greater information about the imaged objects themselves.
References:


